EMISSION ASYMMETRY AND TIME DELAYS IN NON-IDENTICAL PARTICLE FEMTOSCOPY*

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Non-identical particle femtoscopy measures the size of the system emitting particles in heavy-ion collisions as well as the difference between mean emission space-time coordinates of two particle species ("emission asymmetry"). Hydrodynamic models predict a significant emission asymmetry between pions and kaons, coming from collective flow, enhanced by contribution from flowing resonances. We present calculations of pion–kaon, pion–proton, and kaon–proton femtoscopic correlations within the (3+1)D hydrodynamic model coupled to statistical hadronization code THERMINATOR 2, corresponding to Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. We show the extracted system size and emission asymmetry. Recently, the ALICE Collaboration presented results on kaon femtoscopy which suggest that there is a delay in emission time of kaons of the order of 2 fm/c. It is interpreted as a signature for the existence of extended hadronic rescattering phase in Pb–Pb collisions at the LHC and, in particular, the importance of the rescattering via the K^* resonance. We discuss the influence of emission time delays on the extracted system size and emission asymmetry. We propose a sensitive and independent experimental test to confirm the existence of kaon emission time delay (and, consequently, the existence of rescattering via the K^* resonance) based on the femtoscopic correlations for non-identical particles.

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1. Introduction

The heavy-ion collisions at ultra-relativistic energies are used to study the new phase of strongly interacting matter — the Quark–Gluon Plasma (QGP), where quarks and gluons are the relevant degrees of freedom. In the Pb–Pb collisions at the Large Hadron Collider, the created system stays in

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the QGP phase for a time of the order of 10 fm$/c$, after which the hadronization occurs. Later, hadrons interact with each other in the so-called "rescattering" phase. Several observables which are used to study the QGP are also influenced by the "rescattering" phase. It is, therefore, important to characterize it in detail and, in particular, to confirm its existence and to determine its duration.

In the recent work [1], it is argued that pion–kaon correlations may provide an observable, which can give information on the rescattering phase. Non-identical particle femtoscopy was originally proposed as a probe of differences of average emission times of two particle species [2]. Later, it was shown [3] that it is also sensitive to asymmetries arising from radial flow. In heavy-ion collisions at the RHIC energies, both types of asymmetries ("time" and "flow") are present, they both contribute to the measured asymmetry, but the flow asymmetry is the dominant one [4].

The ALICE Collaboration has measured in detail the femtoscopic correlation functions for identical pions [5] and kaons [6]. The models, which include the QGP phase modeled in the hydrodynamic framework, predict trends such as the growth of the system size with event multiplicity and decrease of the apparent system size with pair transverse momentum. They are observed in data. However, it was found that system sizes measured for pions and kaons do not follow a common "$m_{\rm T}$ scaling" curve. Instead, kaon radii are larger than the ones for pions at similar $m_{\rm T}$ [6]. This is interpreted by ALICE as a consequence of the hadronic rescattering phase. Specifically, the rescattering of kaons via the K^* resonance introduces emission time delay, which, in turn, increases the apparent source size for kaons.

In [1], it is argued that such average emission time delay for kaons should be directly measurable in the pion–kaon femtoscopic correlation function. In particular, the additional 2 fm$/c$ delay in kaon emission time decreases the observed pion–kaon emission asymmetry from approximately 6 fm to approximately 4 fm for most central Pb–Pb collisions at the LHC energies. An experimental observation of such effect would be a strong argument for the importance of the hadronic rescattering phase in such collisions.

The argument above has one limitation. It relies on the correctness of the modeling of the QGP phase and the accurate prediction of the pion–kaon emission asymmetry from the model. It then takes this prediction, modifies it with an additional effect (kaon emission delay) and only this final number is compared with the data. One might argue that an agreement of the prediction with the data is not evidence for the existence of time delay, but rather a symptom of the incorrect modeling of the QGP phase. A possible counter-argument would be that the same model correctly describes the pion femtoscopic data. However, an independent, preferably data-driven and based on the same non-identical femtoscopic technique confirmation of the correctness of the QGP modeling would be desirable.

In this work, we propose such a measurement. The time delay mentioned by ALICE concerns only kaons. The K^* decays into a pion as well, but the percentage of pions coming from this resonance is so small that they do not influence the pion average emission time significantly. Therefore, the measurement of the pion–proton femtoscopic correlation should not be influenced by this delay, while the kaon–proton femtoscopic correlation should be affected, providing an independent measurement of the delay. In other words, we propose to perform three measurements: pion–kaon, pion–proton, and kaon–proton femtoscopic functions. The emission asymmetry of the first and the third measurement should be affected by the emission time delay for kaons, while the second one constitutes a "zero-delay" cross-check.

2. Non-identical correlations simulation

We perform the calculation of the femtoscopic correlation functions on events simulated with the THERMINATOR 2 statistical hadronization, resonance decay and propagation code [7], coupled to (3+1)D hydrodynamic model of the system evolution [8]. The details of the simulation are described in [1], we use identical data sample here. The generated events correspond to Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, with centrality intervals of 0–10%, 10–20%, 20–30%, 30–40%, and 40–50%.

The femtoscopic correlation functions are calculated based on these events, using the weight formalism presented in detail in [1, 4, 9]. For the pair weight, we only consider the Coulomb interaction, both in the calculation of the correlation function, as well as in the fitting procedure. This is an acceptable simplification for all pair types, except opposite-sign kaon–proton pairs, where the strong interaction is significant. For these pairs, the presented femtoscopic correlation function cannot be directly compared to data, however, the extracted source parameters can still be used. Example correlation function for all pair types and both charge combinations are shown in Fig. 1. As expected, the same-sign pairs shown negative correlation effect, while the opposite-sign show positive correlation, coming from Coulomb repulsion and attraction, respectively. The kaon–proton pair has significantly smaller Bohr radius, resulting in significantly wider correlation effect, as compared to the pion–proton and pion–kaon pairs. The real part of the $l = 1$, $m = 1$ component of the spherical harmonics decomposition of the correlation function differs from zero for all pair types, indicating a non-zero emission asymmetry in all cases.

The calculated correlation functions are fitted in a procedure closely resembling the experimental one, described in [1]. A system size and emission asymmetry is extracted for each charge combination of each pair type. For a given centrality and pair type, the extracted source sizes for all charge

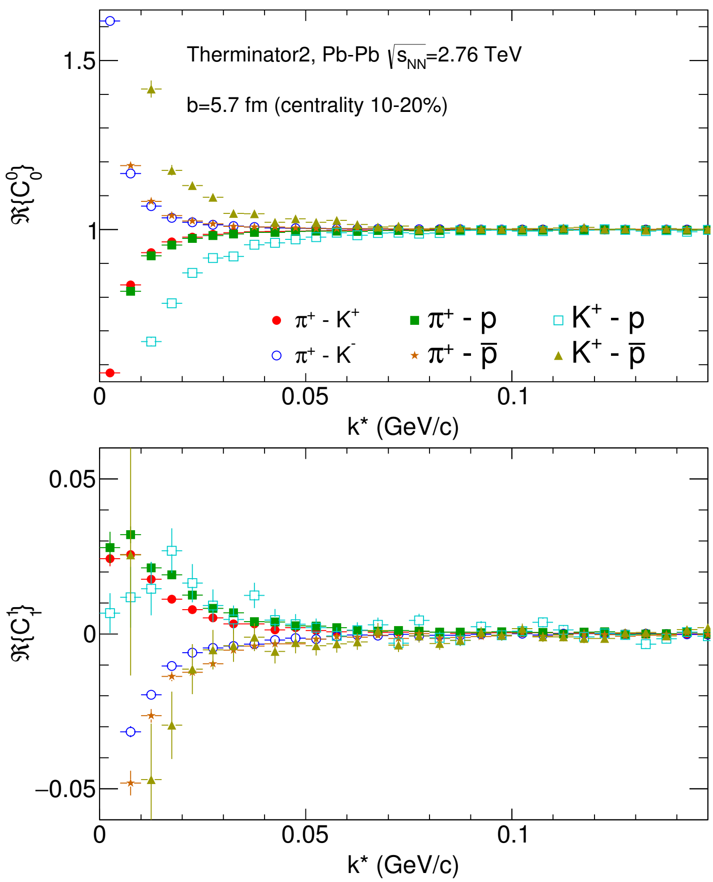

Fig. 1. Example correlation functions for Coulomb-only same-sign and opposite-sign charge combinations for pion–kaon, pion–proton and kaon–proton pairs.

combinations are combined to give one value per centrality and pair type. Similar averaging is performed for emission asymmetry. The resulting averaged source parameters are shown in Fig. 2.

The two-particle source size extracted from the non-identical particle femtoscopic correlation is the convolution of the single-particle source sizes for the two particles. The "$m_{\rm T}$ scaling" predicts that the pion source will be significantly larger than the kaon or proton source at similar particle velocity. Therefore for pion–kaon and pion–proton correlations, the pion source will dominate, while kaon source will also be larger than the proton one. This is seen in the upper panel of Fig. 2, where pion–kaon and pion–proton sources are significantly larger than the kaon–proton one. The source sizes for all pairs also seem to grow linearly with the average particle multiplicity density.

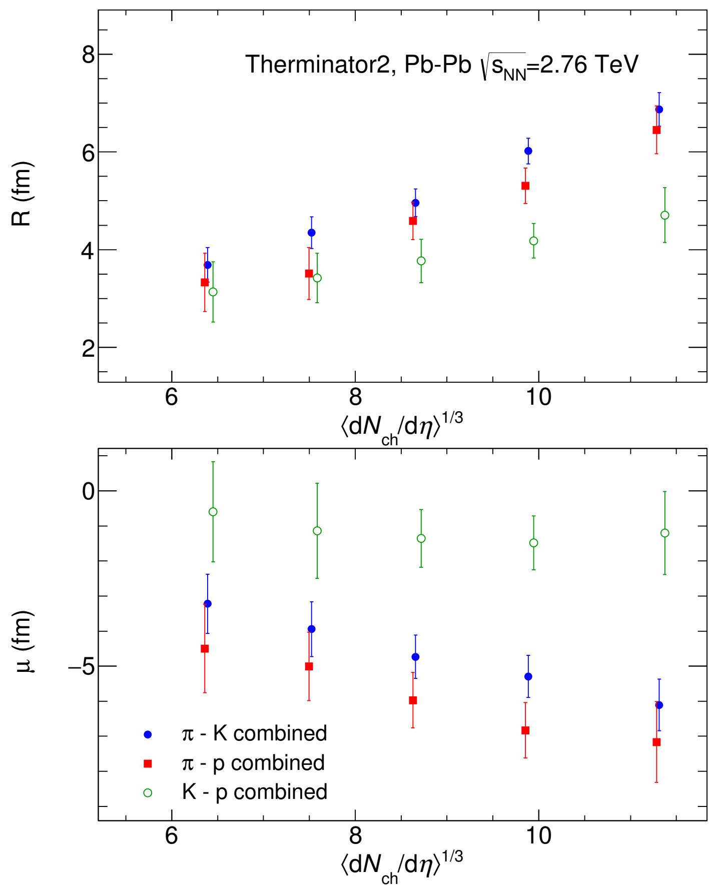

Fig. 2. Source radius and emission asymmetry extracted from pion–kaon, pion–proton, and kaon–proton correlations as a function of centrality.

The emission asymmetry in the flow-dominated picture reflects the shift of the particle emitting region to the edge of the source as the particle mass increases [4]. As a consequence, in Fig. 2, the largest asymmetry is for the pair with largest mass difference: the pion–proton. The kaon–proton asymmetry, on the other hand, is relatively small, and comparable to the difference between the pion–proton and pion–kaon emission asymmetries. All asymmetries have negative values, indicating that the lighter particle (which is always taken as first in the pair) is emitted closer to the center of the system. The absolute value of asymmetry grows with event multiplicity for pion–kaon and pion–proton pairs. These calculations are the baseline predictions for emission asymmetries for all pair types. They do not include the time delay for kaons. If such delay is indeed present in data, then pion–

kaon and kaon–proton asymmetry should be affected, while the pion–proton asymmetry should remain unchanged, serving an independent cross-check of this interpretation.

3. Summary

We present simulations of pion–kaon, pion–proton, and kaon–proton correlation functions for Pb–Pb collisions at the LHC energies, simulated in the hydrodynamic code. They provide an important baseline for comparison with experimental data. In particular, the existence of the emission time delay for kaons can be searched for with such comparison. In particular, the calculations for pion–proton pairs should not be sensitive to such a time delay, serving as an independent validation of the underlying theoretical scenario, where the QGP phase is followed by hadronic rescattering.

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